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Bottom production from fixed-target to LHC energies

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Abstract

We present a state-of-the-art compilation of the existing bottom production cross sections in elementary collisions, from fixed-target to collider experiments. We then discuss the theoretical uncertainties on the total and differential bottom cross sections in the FONLL approach. In particular, we show total cross sections and kinematical distributions of the bottom hadrons and their decays: $B \to e/\mu X$, $B \to D \to e/\mu$, and $B \to J/\psi X$. After seeing that the calculations give a good description of the existing measurements, we present detailed predictions for the LHC experiments in their specific phase space windows.

Keywords: perturbative QCD, heavy-ion collisions, FONLL

1. Introduction

Recent improvements in heavy quark production theory and experimental measurements at colliders, especially for bottom production, have shown that the perturbative QCD framework seems to work rather well, see Refs. [1, 2]. It is important to continue to validate this theoretical framework and its phenomenological inputs, extracted from other measurements, with new data such as that obtained by the CMS collaboration in pp collisions at $\sqrt{s} = 7$ TeV [3]. We validate the FONLL approach with lower energy data and also compare the results with preliminary LHC data. By showing good agreement between the calculations and the data, we demonstrate we can confidently extrapolate our results to energies appropriate for heavy-ion measurements.

2. Benchmark Calculations

We calculate the transverse momentum (p_T) and pseudorapidity distributions of bottom quarks, bottom hadrons resulting from fragmentation and, finally, the muons and J/ψ's produced in semi-leptonic B decays [4]. Theoretical uncertainties are estimated as extensively as possible.

The prediction of final-state observables in decays of heavy-flavor hadrons produced in pp collisions includes three main components: the p_T and pseudorapidity distributions of the heavy quark Q, calculated in

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perturbative QCD; fragmentation of the heavy quarks into heavy hadrons, H_Q, described by phenomenological input extracted from e^+e^- data; and the decay of H_Q into the final state according to spectra available from other measurements. This cross section is schematically written as

$$\frac{Ed^3\sigma(F)}{dp^3} = \frac{E_Q d^3\sigma(Q)}{dp_Q^3} \otimes D(Q \to H_Q) \otimes f(H_Q \to F) \tag{1}$$

where the symbol $\otimes$ denotes a generic convolution and F represents the final state muon or J/ψ. The decay spectrum, $f(H_Q \to F)$, accounts for the branching ratios.

The distribution $Ed^3\sigma(Q)/dp_Q^3$ is evaluated at Fixed-Order Next-to-Leading-Log (FONLL) [5]. As in Ref. [4], we take $m_b = 4.75$ GeV as the central mass value and vary the mass between $4.5 < m_b < 5$ GeV to estimate the uncertainty due to quark mass. The perturbative calculation also depends on the factorization (μ_F) and renormalization (μ_R) scales. The scale sensitivity is a measure of the perturbative uncertainty. We take $\mu_{R,F} = \mu_0 = \sqrt{p_{\rm T}^2 + m_b^2}$ as the central value of the scales and vary μ_F and μ_R independently within a 'fiducial' region defined by $\mu_{R,F} = \xi_{R,F} \cdot \mu_0$ with $0.5 \leq \xi_{R,F} \leq 2$ and $0.5 \leq \xi_R/\xi_F \leq 2$ so that $\{(\xi_R, \xi_F)\} = \{(1,1), (2,2), (0.5,0.5), (1,0.5), (0.5,1), (2,1), (1,2)\}$.

Our final prediction is thus an uncertainty band which has a reasonably large probability of containing the 'true' theoretical prediction. The envelope containing the resulting curves defines the uncertainty. The mass and scale uncertainties are added in quadrature so that

$$d\sigma_{\rm max/min} = d\sigma_{\rm cent} \pm \sqrt{(d\sigma_{\mu,{\rm max/min}} - d\sigma_{\rm cent})^2 + (d\sigma_{m,{\rm max/min}} - d\sigma_{\rm cent})^2} \tag{2}$$

where the subscript "μ, max/min" indicates the maximum/minimum value of the cross section obtained for the central mass for all allowed scales and "m, max/min" is the max/min cross section over the range of mass values with $\xi_F = \xi_R = 1$ and the $+/-$ sign goes with max/min, respectively. The bottom quark mass is large enough for the strong variations in the low x gluon distribution and the size of α_s apparent in charm production [6] to be considerably reduced.

The fragmentation function, $D(b \to B)$, where B indicates a generic admixture of bottom hadrons, is consistently extracted from e^+e^- data in the context of FONLL. Bottom fragmentation depends on the parameter α in the functional form suggested by Kartvelishvili *et al.* [7]: $\alpha = 29.1$ for $m_b = 4.75$ GeV, $\alpha = 34$ for $m_b = 5$ GeV, and $\alpha = 25.6$ for $m_b = 4.5$ GeV (see Ref. [8]).

The measured spectra for primary $B \to \mu$ decays are assumed to be equal for all bottom hadrons. The contribution of muons from secondary B decays, $B \to D \to \mu$, was obtained by convoluting the $D \to \mu$ spectrum with a parton-model prediction of $b \to c$ decay. The resulting secondary muon spectrum is very soft, giving a negligible contribution to the total. The decay spectra are normalized using average branching ratios for admixtures of bottom hadrons [9]: BR($B \to \mu$) = 10.99±0.28% and BR($B \to D \to \mu$) = 9.6±0.6%.

The calculated bottom quark production cross section, with its uncertainty, is plotted in Fig. 1 as a function of the pp $\sqrt{s}$. The available experimental measurements [10, 11, 12, 13, 14], also shown, are in agreement with our calculation. The CDF $p\bar{p}$ results [15] correspond to a limited coverage in rapidity and $p_{\rm T}$, as indicated, and specific FONLL calculations have been made, applying the same phase-space cuts.

3. Comparison to Preliminary LHC Data

We now compare our FONLL calculations to the preliminary CMS data in pp collisions at 7 TeV [16, 17]. Our results for muons from b decays in the CMS acceptance, $p_{\rm T}^\mu > 6$ GeV and $|\eta^\mu| < 2.1$, are shown in Fig. 2. We note that since the reported experimental values are for all muons, $\mu^+ + \mu^-$, the FONLL result, normalized to the total cross section, corresponding to $(\mu^+ + \mu^-)/2$, must be multiplied by two.

We now calculate the fraction of J/ψ production coming from B decays at 7 TeV. We will also compare our results with the CDF measurement [15]. The prompt inclusive J/ψ yield is calculated in the Color Evaporation Model (CEM). In the CEM, quarkonium production is treated as $c\bar{c}$ below the $D\overline{D}$ threshold,

$$\sigma_Q^{\rm CEM} = F_Q \sum_{ij} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \int dx_1\, dx_2\, f_{i/p}(x_1, \mu^2)\, f_{j/p}(x_2, \mu^2)\, \hat{\sigma}_{ij}(\hat{s})\, \delta(\hat{s} - x_1 x_2 s) \; . \tag{3}$$

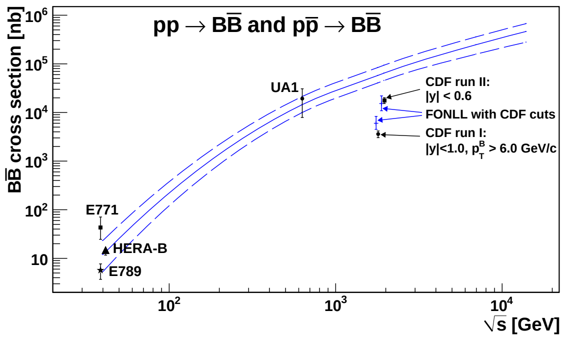

Figure 1: The total $b\bar{b}$ cross section as a function of $\sqrt{s}$ in pp collisions compared to data [3]. The solid curve shows the FONLL central value while the dashed curves delimit the uncertainty band. The limited-acceptance CDF results from $p\bar{p}$ collisions [3] are also shown. The corresponding FONLL calculations are shown as points with error bars (displaced left).

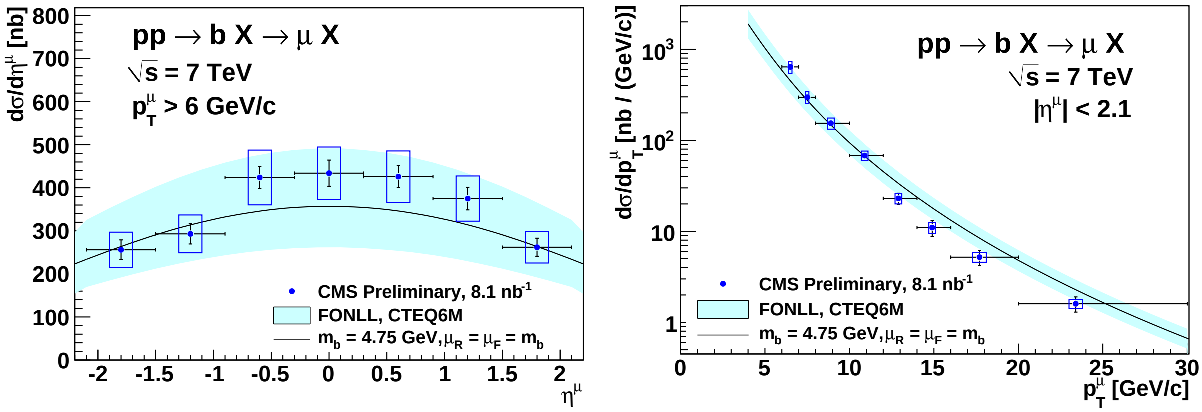

Figure 2: The theoretical uncertainty bands and CMS preliminary results for $pp \to bX \to \mu X$ at $\sqrt{S} = 7$ TeV [16]. Left: The η distribution for $p_T^\mu > 6$ GeV. Right: The p_T distribution for $|\eta^\mu| < 2.1$.

The different charmonium states are assumed to have the same $\sqrt{s}$, p_T and x_F dependence. The normalization, F_Q, is determined by comparison to the J/ψ production cross section as a function of $\sqrt{s}$ [18].

The B-fraction is the ratio of inclusive J/ψ production coming from B meson decays to the total inclusive prompt J/ψ production. The J/ψ yield is the sum of the $B \to J/\psi$ decays, calculated with FONLL, and direct, prompt J/ψ production, calculated in the CEM,

$$B\,\text{fraction} \equiv \frac{B \to J/\psi X}{\text{prompt, inclusive}\, J/\psi + B \to J/\psi X}\,.$$

The results are shown in Fig. 3. The left-hand side of Fig. 3 shows the B fraction for pp collisions at 7 TeV in two different rapidity ranges of the CMS acceptance. The preliminary CMS results are shown in blue for the central rapidity region, $|y| < 1.4$, and grey for the more forward region, $1.4 < |y| < 2.4$ [17]. The shaded areas show the uncertainty on the calculated fraction. Only the uncertainty on the FONLL $B \to J/\psi$ calculation is shown. The right-hand side of Fig. 3 compares the CDF Run II results ($p\bar{p}$ at 1.96 TeV, $|y| < 0.6$) [15] to the FONLL + CEM calculations. While curvature of the calculated fraction as a function of p_T appears to differ from that of the data, the results are in agreement for $p_T \leq 12$ GeV/c.

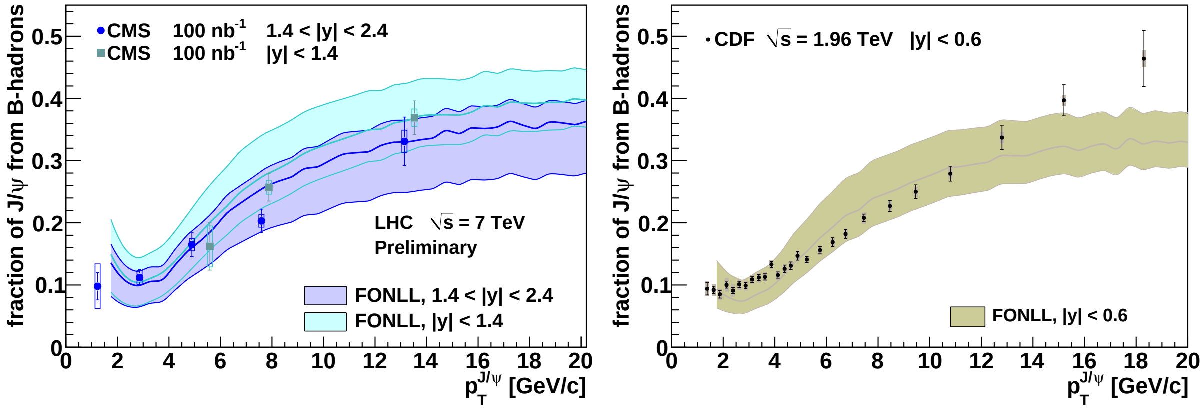

Figure 3: The theoretical uncertainty bands for the $B \to J/\psi$ fraction as a function of p_{T} compared to data. Left: The CMS results from pp collisions at $\sqrt{s} = 7$ TeV in the ranges $y < 1.4$ and $1.4 < y < 2.4$ [17]. Right: The CDF Run II results for $p\overline{p}$ collisions at 1.96 TeV in $y < 0.6$ [15].

4. Summary

Total cross section calculations using the FONLL approach for $pp \to B\overline{B}$ show excellent agreement across a wide range of $\sqrt{s}$ at both full phase space and CDF phase space. This provides confidence that extrapolating to LHC energies will also show good agreement. Differential cross section FONLL calculations ($d\sigma/dp_{\mathrm{T}}$ and $d\sigma/d\eta$) at 7 TeV have been compared to preliminary CMS results. The agreement is quite striking. In addition, B fraction calculations have been made that also compare well to the CMS data. This should allow us to expect good agreement between further FONLL calculations and other observables.

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